An Integrated Modeling and Observational Study of Three-Dimensional Upper Ocean Boundary Layer Dynamics and Parameterizations

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Grants #'s: N00014-05-1-0329, N00014-05-1-0330, N00014-05-1-0331
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LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:

- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior.

OBJECTIVES

Existing high resolution regional models typically resolve the mean vertical structure of the upper ocean boundary layer. Physically-based parameterizations of vertical fluxes make it possible to account for subgrid mixing at length scales smaller than the layer depth, but no specialized parameterization is used to represent the dynamics of horizontal mixing below the O(1)*km* - O(10)*km* resolution scale. We aim to determine the physical limitations of subgrid parameterization on these scales. This project addresses the following questions:

- What physics govern horizontal and vertical mixing in the presence of horizontal variability on the 1-10 km scale?
- What is the relative importance of horizontal and vertical mixing in determining the structure of the boundary layer?
- How well can existing parameterizations simulate vertical and horizontal mixing?
- What physics should be included to improve parameterizations?

APPROACH

An adaptive measurement program employed acoustically-tracked, neutrally buoyant Lagrangian floats and a towed, undulating profiler to investigate the relative importance of vertical and horizontal mixing in governing boundary layer structure in the presence of O(1 km) scale horizontal variability.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE
An Integrated Modeling And Observational Study Of Three-Dimensional Upper Ocean Boundary Layer Dynamics And Parameterizations

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Washington,Applied Physics Laboratory,1013 NE 40th St.,Seattle,WA,98105-6698

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
Existing high resolution regional models typically resolve the mean vertical structure of the upper ocean boundary layer. Physically-based parameterizations of vertical fluxes make it possible to account for subgrid mixing at length scales smaller than the layer depth, but no specialized parameterization is used to represent the dynamics of horizontal mixing below the O(1)km - O(10)km resolution scale. We aim to determine the physical limitations of subgrid parameterization on these scales.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**9**	

Remotely sensed sea surface temperature and ocean color, combined with rapid, high-resolution towed surveys and model results guide float deployments to key locations within fronts. Synoptic, high-resolution surveys followed Lagrangian float drifts to characterize three-dimensional variability within the span of a model grid points. Acoustic tracking allowed towed surveys to follow floats and geolocated all observational assets for later analysis. Measurements characterized boundary layer turbulence and facilitate detailed separation of vertical and horizontal processes.

A turbulence-resolving Large Eddy Simulation (LES) was used to model the dynamics of vertical and horizontal mixing in a domain volume corresponding to a regional model's horizontal gridscale and set in the translating Lagrangian reference frame of the float/survey observations. The observations will provide realistic initial and time-dependent boundary conditions and, in particular, time-dependent lateral boundary conditions will be determined from rapid surveys.

Quantitative one-to-one statistical comparisons between LES results and the float and survey observations will be made. This product will have direct application to assessing regional model subgrid parameterizations.

WORK COMPLETED

The 2006 Measurement Program: Observations in the California Current

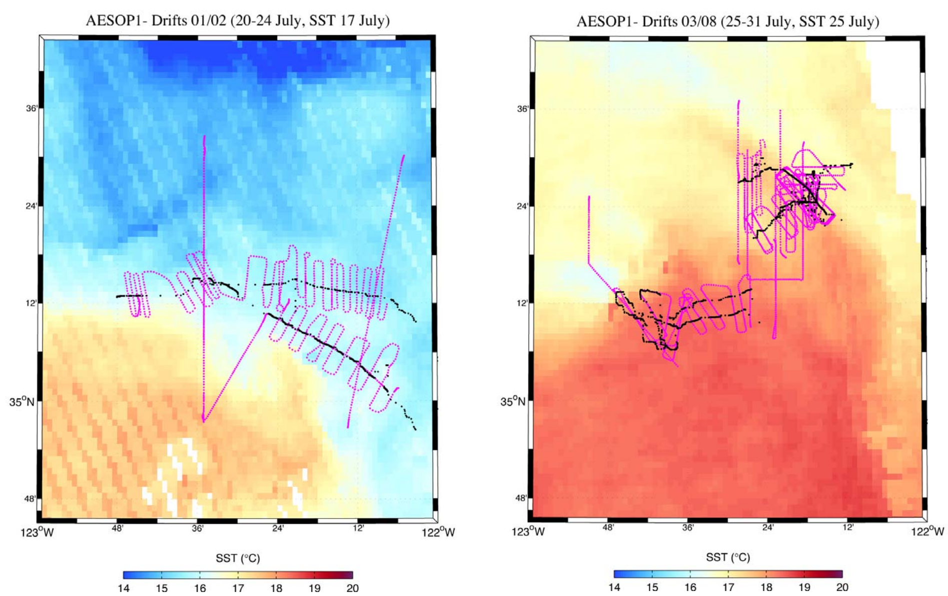

Figure 1. Float drift (black) and towed profiler (magenta) tracks plotted over remotely sensed sea surface temperature. The bathymetry rises from the abyss near the eastern margin of the chart.

The first of two cruises associated with this AESOP effort took place from R/V Roger Revelle, 16 July – 8 August 2006 off the California coast. Operations began with instrument testing and acoustic tracking refinement in the Channel Islands and Santa Barbara channel. Following this, two drifting surveys focused on a zonally oriented front located west of the continental rise off of San Luis Obispo (Fig. 1). A third drift followed the southward flow associated with a strong meridionally oriented front (Fig. 2). Sections occupied prior to float deployment exhibit T-S characteristics, small pycnostads and optical signatures that suggest active subduction of cold-side waters into the region below the warm-side mixed layer base (Fig. 2). Informed by float behavior inferred from model results analyzed before the cruise and by the high-resolution towed profiler section occupied immediately prior to float deployment, we selected a site intended to maximize the probability of observing subduction. Our first few deployments, during periods of weak wind, found little evidence for subduction driven by

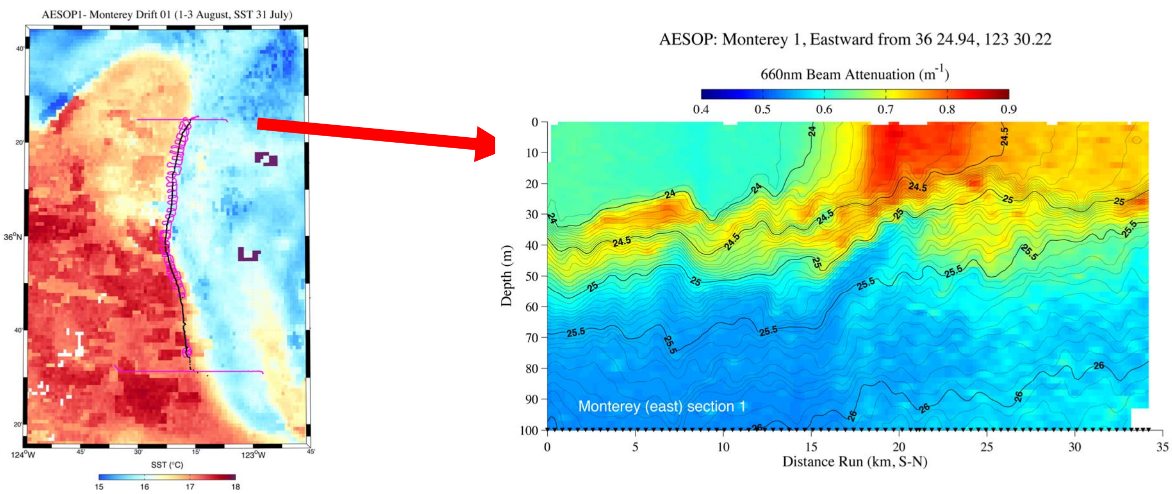

Figure 2. (left) Front-following drift with line colors as defined in Fig. 1. (right) Potential density (contours) and 660 nm beam attenuation (colors) from the section used to choose the float deployment site.

submesoscale processes alone. Our final two deployments, spanning a period of rising, sustained and then relaxing winds, clearly showed subduction and restratification as the front relaxed after the wind dropped.

The 2007 Measurement Program : Observations in the Kuroshio Extension

Building on lessons learned working off the California coast in 2006, the 2007 field effort focused on the strong fronts and submesoscale features associated with the Kuroshio extension. As during the previous cruise, near-realtime remotely sensed images and numerical results guided sampling to promising features. This resulted in three surveys, described below.

The first deployment (Fig. 3) was placed nearby in the Kuroshio extension third meander and focused on a meridionally-oriented section of front forced by southerly (up-front) winds. We anticipated, and found, that the upfront winds would drive frontalysis, spreading light, warm-side waters over denser cold-side waters. We hoped that blocking of Ekman transport by the fronts' relative vorticity field would cause downwelling. However, the front remained weak during the roughly four day survey with the float experiencing no downwelling events.

The second survey (Fig. 4) focused on a steep southward meander that NLOM forecasts predicted would detach within a few days time. Strong northerly winds provided frontogenic (downwind) forcing along the western side of the loop and frontolytic (upwind) forcing over the eastern side. The pre-deployment survey revealed strong fronts marking both sides of the feature, with the deepest mixed layers along the western margin. We deployed a float at the strongest gradient region of the front on the western side, calculating that it would transit over the 'U'-shaped path over 3-4 days contrasting the response to down-front and up-front wind forcing. Over four days of weakening winds, the fronts marking both sides of the meander became more diffuse, with a buoyant cap restratifying the mixed layer across the entire feature.

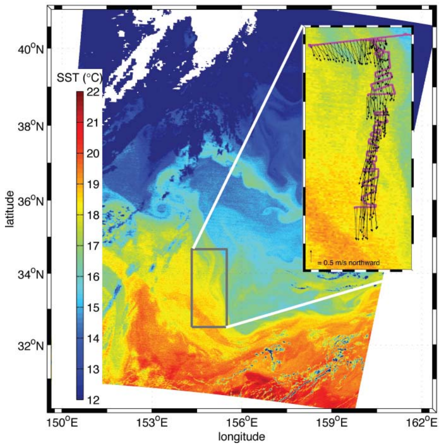

Figure 3. First Kuroshio survey. Colors show MODIS SST image. Inset shows the survey.

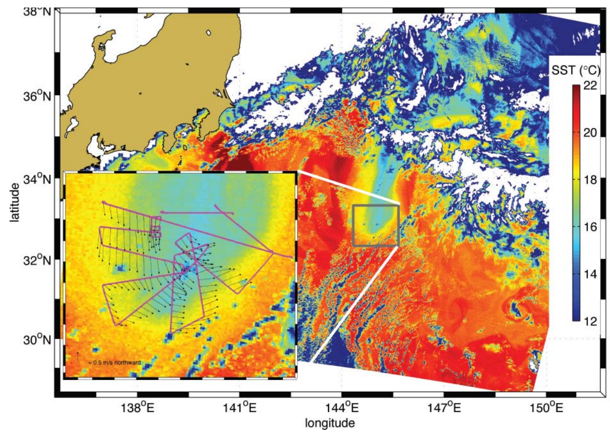

Figure 4. Second Kuroshio survey in a detaching meander – "The Sock"

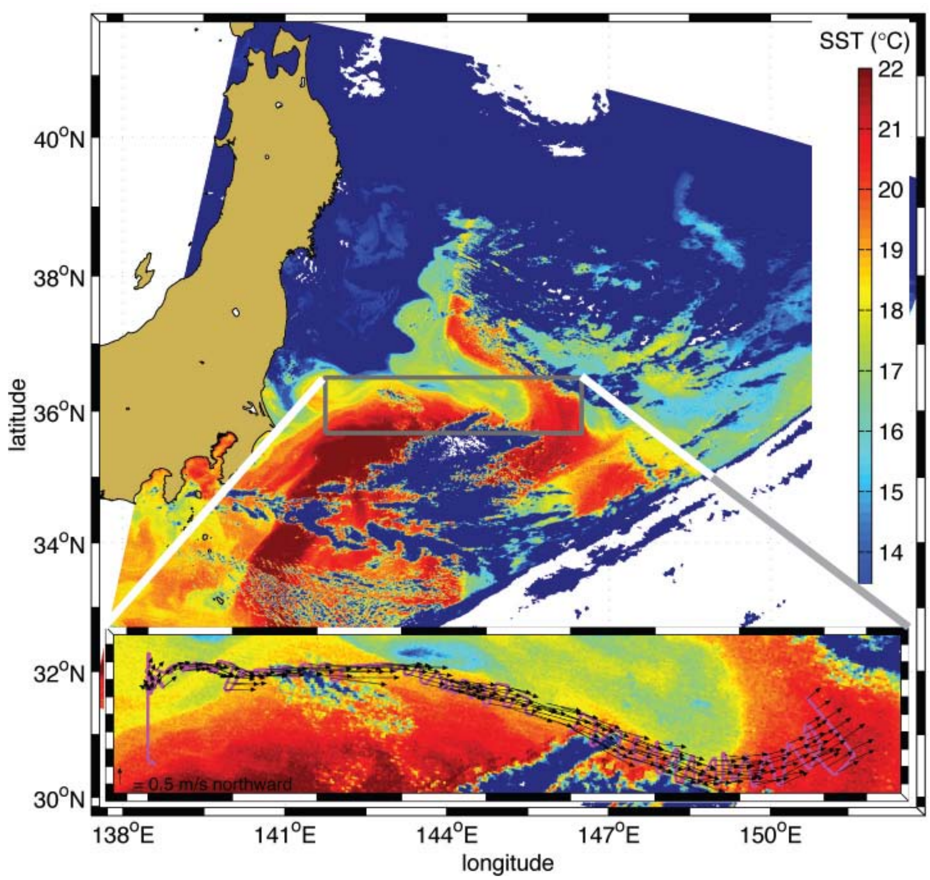

Figure 5. The third survey of the 2007 cruise, focusing on the first section of the Kuroshio extension. The survey (lower insert) followed the front as it is advected westward from its creation off the Japanese coast by the convergence of the cold Oyashio and warm Kuroshio currents.

The final survey focused on the strong, nearly linear , sharp and zonally-oriented section of Kuroshio front extending offshore from Japan (Fig. 5). Forcing by northwesterly (downfront) winds provided an ideal combination. The pre-deployment section revealed intense cyclonic relative vorticity and optical signals indicative of recent subduction in strong gradient region. Over a 7-day period, Triaxus repeatedly occupied cross-front sections following the drifting float, attempting to characterize a region marked by two outcropping isopycnals. Results from this survey are described in detail below.

Data Processing and Analysis

Triaxus towed profiler, float and shipboard data have been processed for both cruises. Triaxus-mounted ADCP data have been processed for the Kuroshio deployment, with efforts on-going to finish processing of the California Current cruise. Analysis efforts have focused on restratification observed at a front in the California Current and on the evolution of a particularly sharp, wind-forced from in the Kuroshio. The 2006 annual report presented early results from the California Current front. Results from one of the Kuroshio surveys are summarized in the next section. Dr. Luc Rainville (a new addition to the Ocean Physics Department at APL-UW), has recently joined our AESOP effort and has made large contributions to the analysis. Analysis efforts, focused on both California Current and Kuroshio deployments, will continue in the coming year.

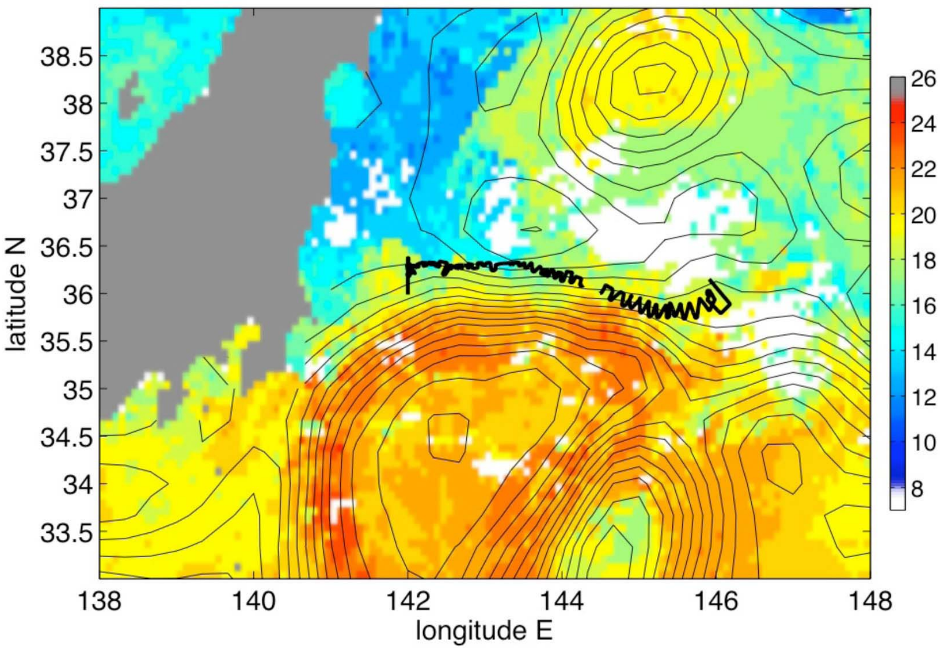

Figure 6. AVISO Sea Surface Height (contours) and MODIS Sea Surface Temperature (colors) for the period of the last Kuroshio survey. A thick black line marks the path sampled by the Triaxus towed profiler as it followed the drifting float.

RESULTS

Here we summarize the evolution of the Kuroshio case.

Evolution of a Sharp Kuroshio Front

The final Kursohio survey focused on the front formed by the confluence of Oyashio (south-flowing, cold) and Kurosho (north-flowing, warm) Currents (Fig. 6). A ~4-day time series of sections characterized frontal evolution in the float-following reference frame (Fig. 7). The sharpest gradients develop around yearday 137, confined to the upper 40 m with weaker contrasts below. Over the next two days, the front weakens (as seen by the steady increase in isothem separation in Fig. 6a and isopycnal separation in Fig. 7c-f) while the mixed layer deepens (Fig. 7c-f).

At the time of the sharpest front, strong (10 – 15 m/s) wind forcing aligns largely down-front (Fig. 8, middle panel). Previous investigations have related down-front oriented wind-forcing to generation of negative potential vorticity (PV), strong frontogenesis, energetic secondary circulation and enhanced rates of vertical exchange (Thomas and Lee, 2005; Lee et al., 2006). The 4-day Kuroshio front

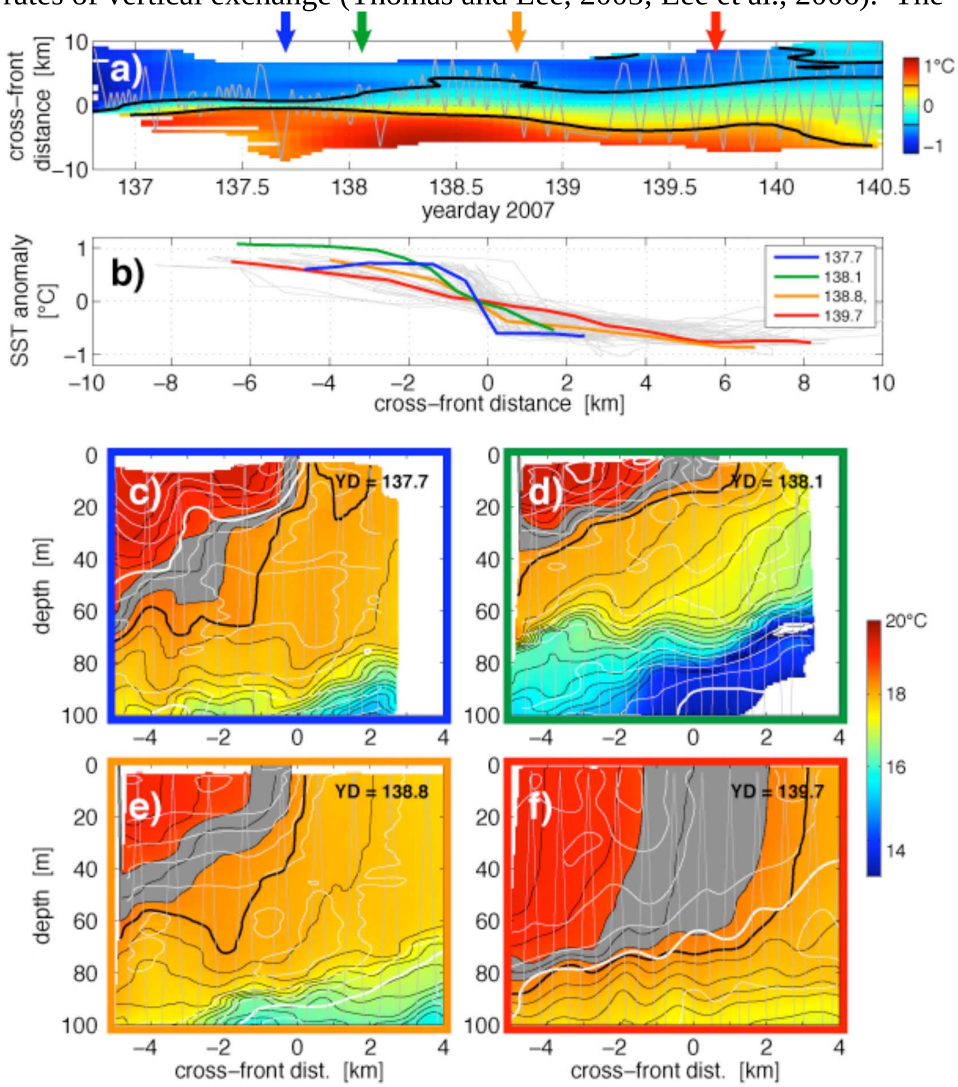

Figure 7. (a) Sea surface temperature anomaly across the front, with black contours marking the ±0.5 °C interval. (b) Time series of temperature anomalies plotted as a function of cross-front distance. (c – f) Time series of sections with potential temperature (color), potential density (black contours) and along-front velocity (white contours). Boarder colors correspond to the lines in (b). The front widens (weakens) and shoals at YD138.1 (d). Over the next day and a half (e-f) the mixed layer deepens while the front continues to widen.

sampling period begins with down-front wind forcing, strong cross-front density gradients in the upper 40 m and negative PV. Down-front winds drive heavy cold-side waters over lighter south-side water, acting on existing meridional density gradients established by confluent flow to rapidly sharpen the front. The resulting intense cross-front density contrasts greatly amplify the tilting term $(\partial u/\partial z)(\partial b/\partial y)$, which drives PV negative and establishes conditions for symmetric instability (Fig. 9). At the end of YD137, the winds turn such that the downfront component weakens, accompanied by rapidly weakening cross-front density gradients (Fig. 8, bottom panel; Fig. 7a,d-e) and PV climbing rapidly to zero (Fig. 8a). The front widens and shoals (Fig. 7c-d) quickly in response to weakening downfront wind, perhaps and indication of energetic lateral mixing. The downfront wind component continues to weaken through the end of the survey, with the front continuing to widen, the mixed layer deepening (Fig. 7e-f) and mixed layer PV remaining at zero (Fig. 8, top panel).

IMPACT/APPLICATION

None.

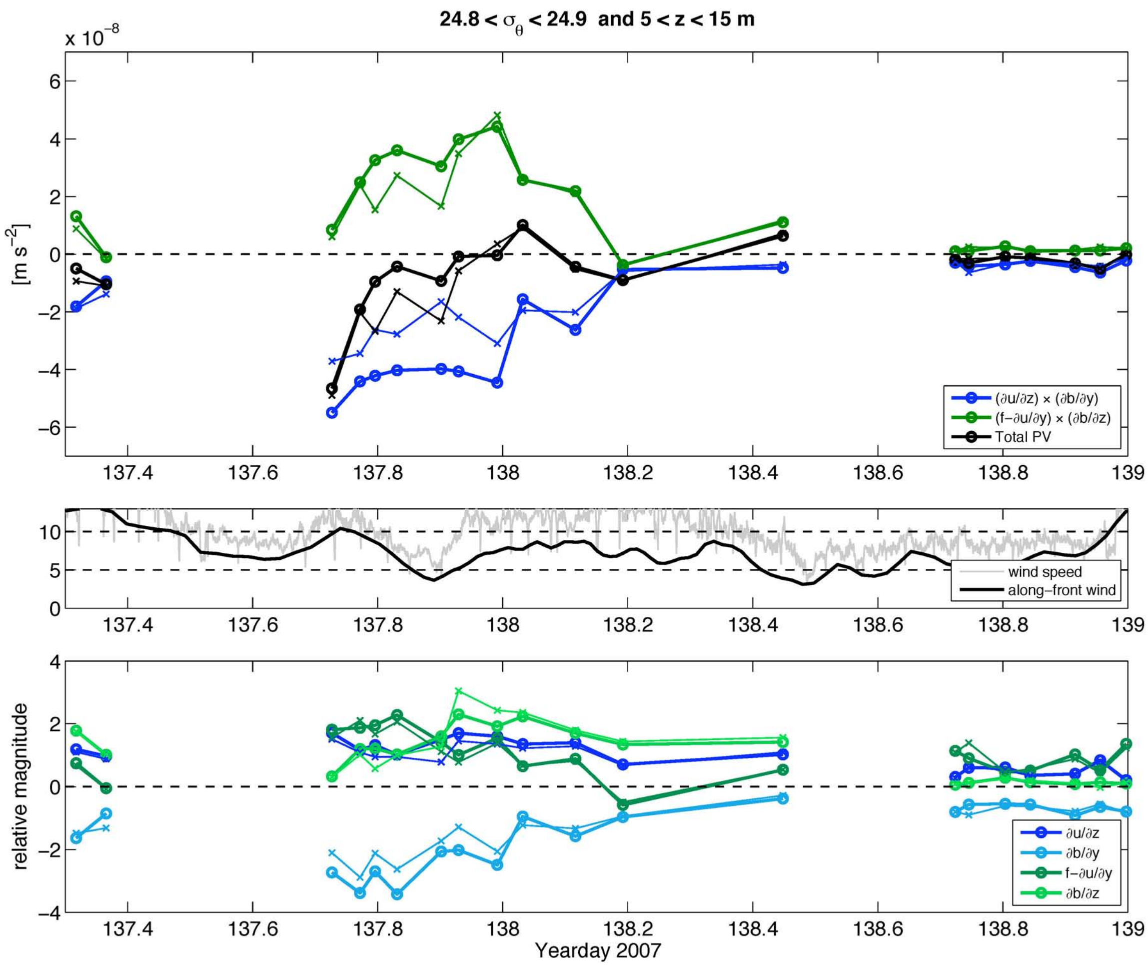

Figure 8. (top) Tilting, planetary and total potential vorticity in the near-surface layer. (middle) Total wind speed and the down-front component of wind velocity. (bottom) Components of the terms in the two-dimensional potential vorticity equation.

TRANSITIONS

None.

RELATED PROJECTS

SeaSoar and Doppler Sonar Spatial Survey of Internal Tide Generation and Mixing, Shaun Johnston and Daniel Rudnick.

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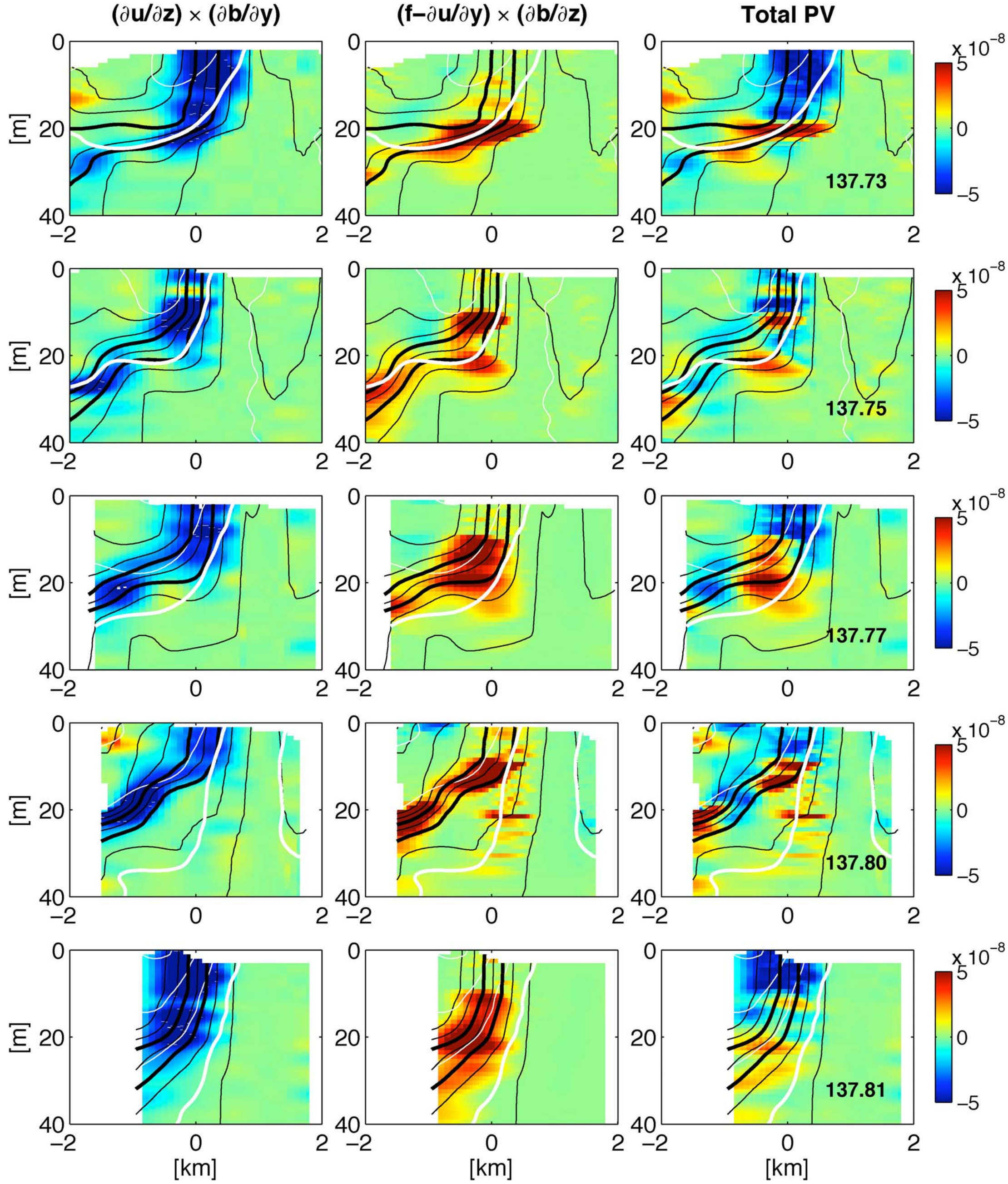

Figure 9. Tilting (left), planetary(center) and total (right) potential vorticity for four sections occupied during the period of strong down-front wind forcing. The tilting term drives negative PV, with the planetary term acting to balance at the mixed layer base. This confines negative total potential vorticity to a thin (20 m) near-surface layer at the region of the sharpest lateral density contrast.

PUBLICATIONS

None.